Computer Simulation of Cooling Effect of Wind Tower on Passively Ventilated Building

John Seryak, Project Engineer
Kelly Kissock, Associate Professor
Department of Mechanical and Aerospace Engineering
University of Dayton
Dayton, Ohio

ABSTRACT

Traditional buildings are cooled and ventilated by mechanically induced drafts. Natural ventilation aspires to cool and ventilate a building by natural means, such as cross ventilation or wind towers, without mechanical equipment. A simple computer program was developed to simulate airflow through a wind tower based on tower dimensions and air temperature. The program was compared to experimental results with reasonable agreement. Parametric analysis indicates that interior air temperature approaches outdoor air temperature asymptotically as tower height and cross-sectional area are increased, and that it may be more cost effective to increase the tower's height than its cross sectional area. The program was then used to simulate hour-by-hour indoor air temperatures of an occupied auditorium in Dayton, OH. The results indicate that a large wind tower was able to keep the temperature of an occupied auditorium at a comfortable level year round.

INTRODUCTION

Traditional buildings are cooled and ventilated using mechanical air-conditioning equipment and fans. Natural ventilation aspires to cool and ventilate a building by natural means, without mechanical equipment. Natural ventilation includes cross ventilation via windows, and the use of chimneys, or wind towers, to induce drafts (Short, 1995; Jones and West, 2001).

In this paper, we describe the development of a simplified computer program to simulate the cooling affect of a wind tower on a building with internal heat gains, such as those from occupants or electrical equipment. We then compare simulated results with results from a small-scale physical experiment. Finally, we simulate the interior air temperature of an occupied auditorium on an hour-by-hour basis using TMY2 data for Dayton, Ohio.

SIMPLIFIED MODEL OF BUILDING INTERIOR AIR TEMPERATURE

Assuming steady state conditions, an energy balance of major sensible heat flows into and out of a building yields:

$$\text{Qint} + \text{Qsolar} - \text{Qwindows} - \text{Qwalls} - \text{Qventilation} - \text{Qceiling} = 0 \quad (1)$$

where Qint is internal heat gain from occupants and electrical equipment and Qsolar is solar gain through fenestration. Heat losses through windows, walls and the ceiling are given by:

$$\text{Qwindows} = \text{Awindow} / \text{Rwindow} \times (\text{Ti} - \text{To}) \quad (2)$$

$$\text{Qwalls} = \text{Awall} / \text{Rwall} \times (\text{Ti} - \text{To}) \quad (3)$$

$$\text{Qceiling} = \text{Aceil} / \text{Rceil} \times (\text{Ti} - \text{To}) \quad (4)$$

where A is the cross sectional area and R is the thermal resistance and Ti and To are the indoor and outdoor air temperatures. Heat loss through ventilation, Qventilation is given by:

$$\text{Qventilation} = \text{VFR} \times \rho \times \text{Cp} \times (\text{Ti} - \text{To}) \quad (5)$$

where VFR is the volume flow rate, ρ is the density of air, and Cp is the specific heat of air. We assume that heat gains and losses through the floor, doors, etc. are negligible. Combining and rearranging these equations, gives the interior air temperature, Ti, as:

$$\text{Ti} = (\text{Qint} + \text{Qsolar}) / (\text{Awindow/Rwindow} + \text{Awall/Rwall} + \text{Aceiling/Rceiling} + \text{VFR} \times \rho \times \text{Cp}) + \text{To} \quad (6)$$

SIMPLIFIED MODEL OF INDUCED FLOW THROUGH WIND TOWER

To model air flow through a wind tower, we developed a force balance on the air in the wind tower as shown in Figure 1.

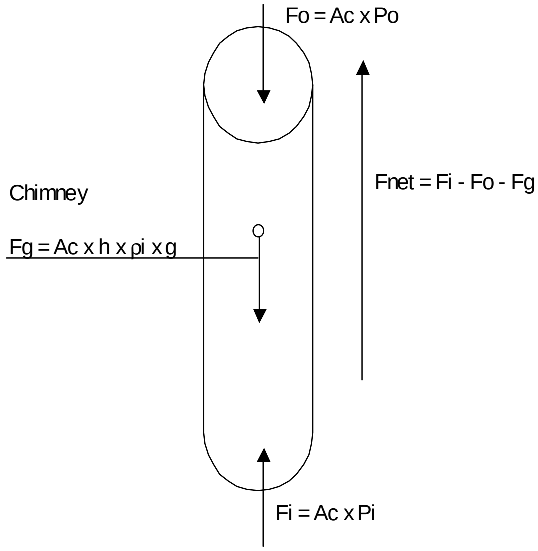

Figure 1. Force balance on air in a wind tower.

The net force upward on the air in the wind tower, Fnet, is:

$$Fnet = Fi - Fo - Fg \quad (7)$$

where Fi and Fo are the forces due to air pressure at the inlet and outlet of the wind tower, and Fg is the force of gravity acting on the column of air in the wind tower as defined below:

$$Fi = Ac \times Pi \quad (8)$$
$$Fo = Ac \times Po \quad (9)$$
$$Fg = Ac \times h \times \rho i \times g \quad (10)$$

where Ac is the cross sectional area of the wind tower, Pi and Po are the air pressures at the inlet and outlet of the wind tower, h is the height of the wind tower, ρi is the density of air in the wind tower and g is the acceleration of gravity. Substituting Equations 8, 9 and 10 in Equation 7 gives:

$$Fnet = Ac \times (Pi - Po) - (Ac \times h \times \rho i \times g) \quad (11)$$

For the stationary air outside the wind tower, Fnet would equal zero, and Equation (11) can be solved for:

$$Ac \times (Pi - Po) = Ac \times h \times \rho o \times g \quad (12)$$

where ρo is the density of air outside of the wind tower. Substituting Equation (12) into Equation (11) gives:

$$Fnet = Ac \times h \times g \times (\rho o - \rho i) \quad (13)$$

From the ideal gas law, we can substitute for ρo and ρi, the density of air outside and inside the wind tower to give:

$$Fnet = Ac \times h \times g \times [Po/(R \times To) - Pi/(R \times Ti)] \quad (14)$$

Dividing by Ac, we obtain the net pressure difference:

$$Pnet = h \times g \times [(Po/To) - (Pi/Ti)] / R \quad (15)$$

Assuming Po and Pi are approximately equal to the average atmospheric pressure, Pbar, gives:

$$Pnet = h \times g \times Pbar \times [(1/To) - (1/Ti)] / R \quad (16)$$

This result is equivalent to the result presented in Jones and West (2001). Pnet can be used in Bernoulli's equation to calculate the velocity, V, and volume flow rate, VFR, of air through the tower as:

$$V = \sqrt{(2 \times Pnet/ \rho)} \quad (17)$$
$$VFR = Velocity \times Ac \quad (18)$$

Equation 18 is substituted into Equation 6 to predict interior air temperature inside a building with a wind tower.

COMPARISON OF EXPERIMENTAL AND THEORETICAL RESULTS

To test the methodology described above, a small physical model was constructed (Karla and King, 1995; Hetrick and Kashuk, 1996) as shown below (Figure 2). The model walls were constructed of plexiglass and the wind tower was constructed from PVC pipe.

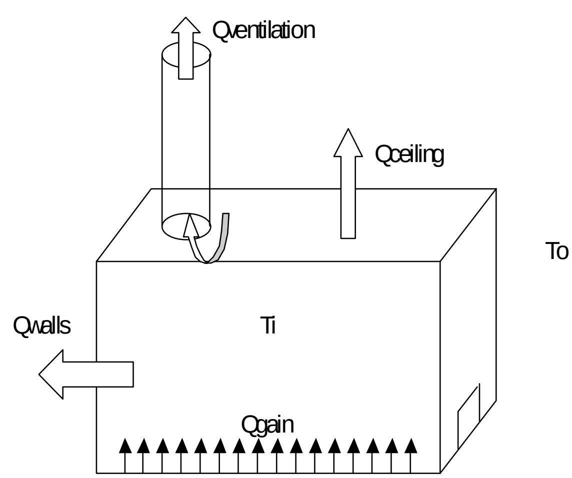

Figure 2. Small-scale physical model of building with internal heat gain and a wind tower.

The dimensions of the model and other important physical parameters are shown in Table 1.

Table 1. Model dimensions and physical characteristics.

Awall (ft^2)	11.88
Aceil (ft^2)	4.375
Achimney (ft^2)	0.084
Height (ft)	2.17
Rwall (hr-ft^2-F/Btu)	0.88
Rceil (hr-ft^2-F/Btu)	0.88

Heat was added to the interior of the model by a light bulb, and later by passing an electrical current through a wire grid over the floor. The air flow through the tower was then measured. Important physical parameters and results are shown in Table 2 (Karla and King, 1995).

Table 2. Important physical parameters and results of experiment to measure air flow through a wind tower from internal heat generation.

Air density (lb/ft^3)	0.07
pxCp (Btu/ft^3F)	0.018
Air gas constant R (ft-lbf/lbm-R)	53.34
Atmospheric pressure (lb/in^2)	14.7
Inside Temperature (F)	87.9
Outside Temperature (F)	72.4
Qint (Btu/hr-ft^2)	115.3
Velocity of air exiting wind tower (ft/s)	2.0

Using the above input data, Equation 6 predicted that the inside air temperature would be 89.5 F (305.1K), which is in close agreement with the measured temperature of 87.9 F (304.2 K). Equation 17 predicted that the velocity of air leaving the tower would be 2 ft/s, which is in reasonable agreement with the measured velocity of 1.4 ft/s.

SIMULATION OF A NATURALLY VENTILATED AUDITORIUM

To investigate the applicability of wind tower ventilation in real buildings, we simulated the auditorium shown in Figure 3.

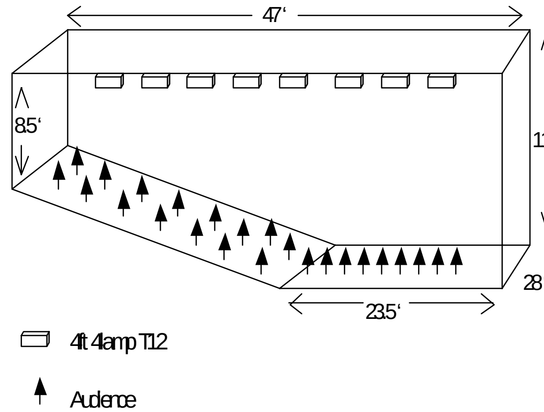

Figure 3. Auditorium with heat gain from 12 fluorescent fixtures and 72 occupants.

We assumed the auditorium is lit by 12 4-ft 4-lamp F40T12 lighting fixtures and that about 72 people occupy the auditorium. Based on these assumptions we estimate the total internal load would be about 32,100 Btu/hr. Assuming the walls of the building are 8" concrete block with 2.5" of face brick, the thermal resistance of the walls would be about 3.815 hr-ft^2-F/Btu. The ceiling was modeled as a 2" slab of concrete with R13 fiberglass batt insulation and a total thermal resistance of about 13.16 hr-ft^2-F/Btu. The dimensions of the auditorium and other important physical parameters are shown in Table 3.

Table 3. Auditorium dimensions and physical characteristics.

Awall (ft^2)	1,570.5
Aceil (ft^2)	1,316
Rwall (hr-ft^2-F /Btu)	3.815
Rceil (hr-ft^2-F /Btu)	13.16

PARAMETRIC EVALUATION OF STACK HEIGHT AND CROSS SECTIONAL AREA

A simulation was run with internal heat gain, but without a wind tower or ventilation to determine the inside temperature. With an outside temperature of 67.7 F (293 K), the inside temperature of the auditorium would be about 130.7 F (328 K). Important physical parameters are shown in Table 4.

Table 4. Important physical parameters

Air density ρ (lb/ft^3)	0.07
Air density x specific heat Cp x ρ (Btu/ft^3F)	0.018
Air gas constant R (ft-lbf/lbm-R)	53.34
Atmospheric pressure (lb/in^2)	14.7

Inside Temperature (F)	131
Outside Temperature (F)	68.1
Qint (Btu/hr-ft^2)	24.4

Using 130.7 F as the inside temperature, a set of simulations were run to determine a range of heights and tower cross-sectional areas that could provide enough ventilation to keep the auditorium at a comfortable temperature. Results showed that the wind tower was able to provide enough ventilation to keep the auditorium cooled to a comfortable temperature. In addition, interior air temperature approaches outdoor air temperature asymptotically as tower height and cross-sectional area are increased (Figure 4).

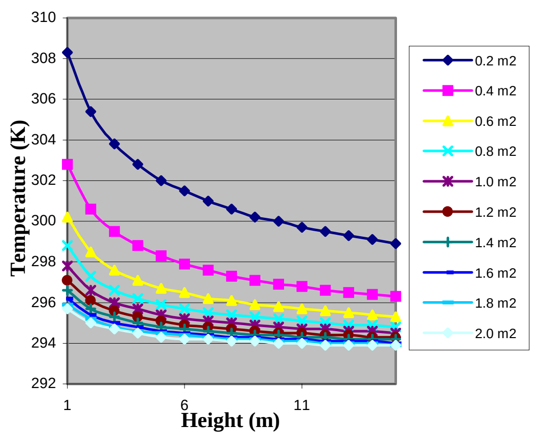

Figure 4. Indoor air temperature for varying tower height and cross-sectional area.

Cross-sectional area and tower height both increase volume flow rate, and thus decrease internal temperature (Table 5). Doubling cross-sectional area results in a greater decrease in temperature than doubling height. However, doubling the cross-sectional area also increases the amount of surface area, or building material, for a wind tower 2.5 times more than doubling the height. Thus, the percentage of temperature decrease compared to the percentage of building material increase is greater for doubling height because increasing height also increases pressure difference. This indicates that in general it would be more cost effective to build up, rather than out.

Table 5. Cross-sectional area and height comparison

Variable Doubled	Ti – To (% Decrease)	Building Material (% Increase)	Ti – To (% Decrease)/ Surface Area (% Increase)
Area	47.6	254	0.19
Height	26.2	100	0.26

ANNUAL THERMAL PERFORMANCE OF AUDITORIUM

The equations presented in the previous sections were developed into a computer model. Air flow through the tower and interior air temperature were then simulated for every hour of the year using TMY2 weather data for Dayton, Ohio. The auditorium was assumed to be continuously occupied. The building was modeled so that when cooling was not needed, a damper would stop air flow through the wind tower. Heating concerns were neglected and only cooling was considered.

Three wind tower sizes where chosen to compare performance. Wind tower A has a cross sectional area of 0.2 m^2, and is 1 m tall, wind tower B has a cross sectional area of 1 m^2 and is 10 m tall, and wind tower C has a cross sectional area of 2 m^2 and is 15 m tall. Simulated hourly inside air temperatures for the three cases are shown in Figure 5.

For a wind tower A, 0.2 m^2 in area, and 1 meter high, satisfactory inside temperatures cannot be maintained during summer months; temperatures are regularly above 90 F, and as high as 115 F (Figure 5A). For the one week period of June 19th through 26th, the inside temperature doesn't dip below 90 F, even at night (Figure 6A). During this week, inside temperatures averaged 27.3 F higher than outside temperatures.

For wind tower B, the inside temperature remains below 75 F for over 85% of the year and rarely exceeds 90 F (Figure 5B). For the one week period of June 19th through 26th, the inside temperature rarely rises above 90 F, in sharp contrast to wind tower A (Figure 6B). During this week, inside temperatures averaged 2.9 F higher than outside air temperatures.

For wind tower C, the inside temperature remains below 75 F for over 87% of the year and rarely exceeds 90 F (Figure 5C). For the one week period of June 19th through 26th, the inside temperature is similar as that in Case B. (Figure 6C). During this week, inside temperatures averaged 1.3 F higher than outside air temperatures.

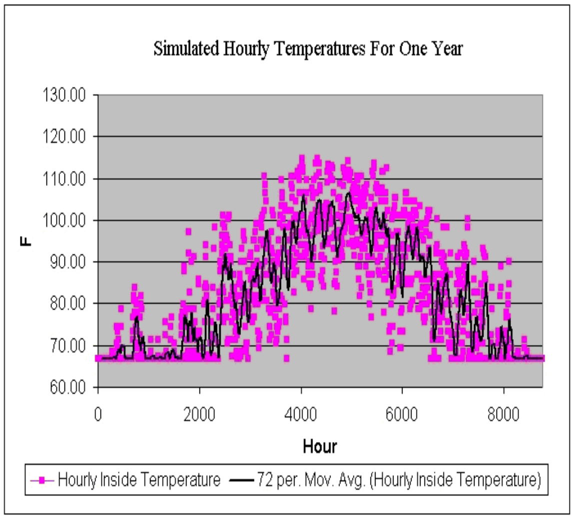

Figure 5A. One year of hourly inside air temperature for building with Tower A in Dayton, Ohio.

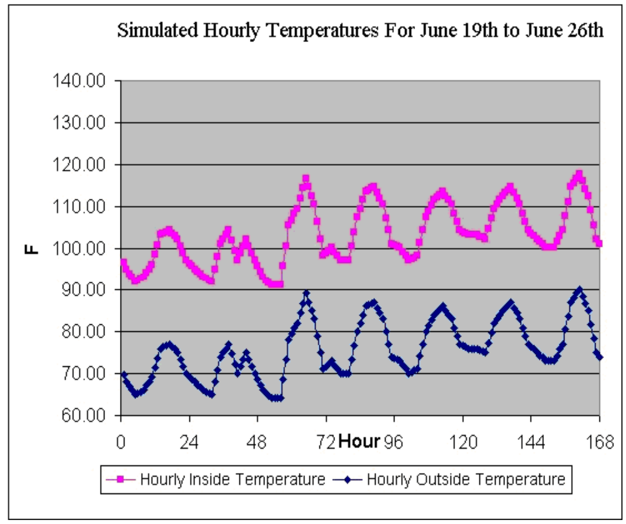

Figure 6A. Inside and outside air temperature for building with Tower A in Dayton, Ohio.

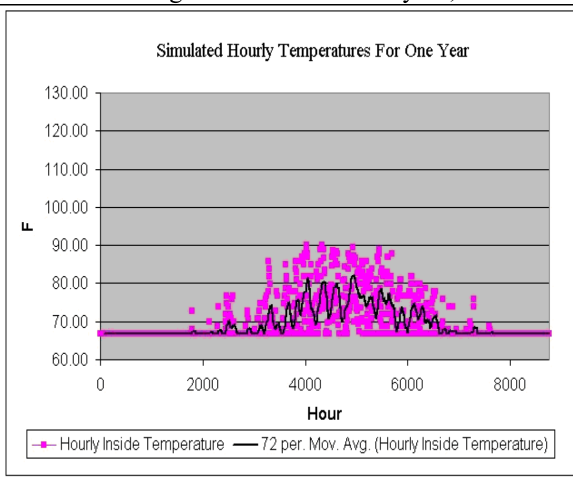

Figure 5B. One year of hourly inside air temperature for building with Tower B in Dayton, Ohio.

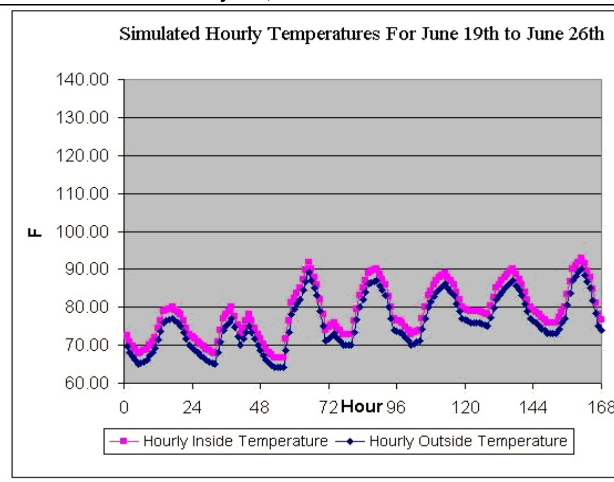

Figure 6B. Inside and outside air temperature for building with Tower B in Dayton, Ohio.

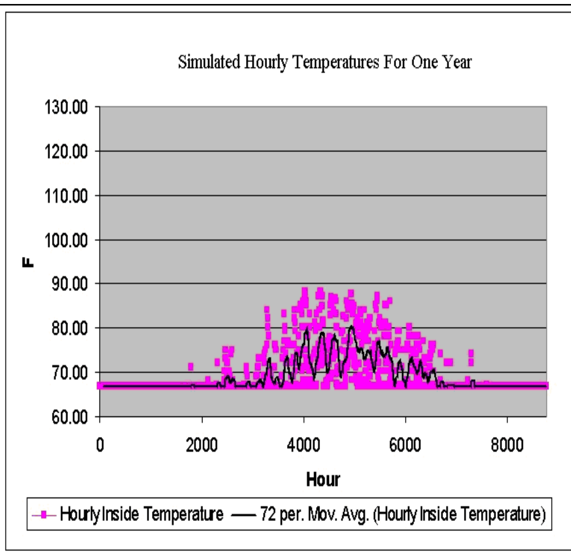

Figure 5C. One year of hourly inside air temperature for building with Tower C in Dayton, Ohio.

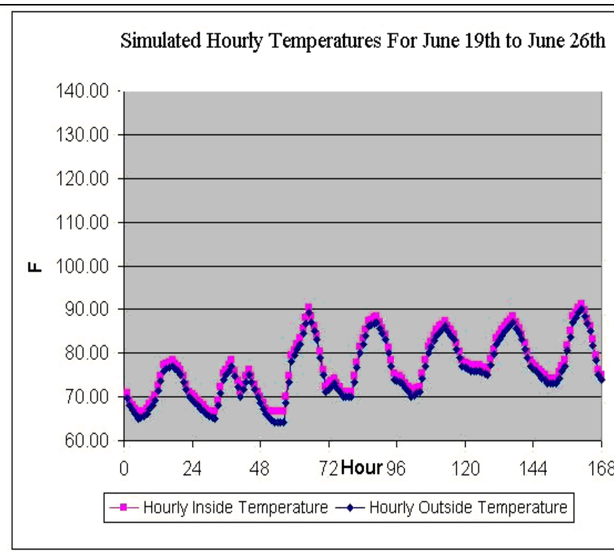

Figure 6C. Inside and outside air temperature for building with Tower C in Dayton, Ohio.

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

The reasonable agreement between a small scale experiment and the simplified air flow and building temperature models developed here suggest that our model may provide an adequate method to approximate real wind tower performance.

Parametric analysis indicates that interior air temperature approaches outdoor air temperature asymptotically as tower height and cross-sectional area are increased. This suggests that wind towers may provide adequate cooling for buildings with internal loads in moderate climates where outside air temperatures remain near the comfortable range.

Doubling cross-sectional area results in a greater decrease in temperature than doubling height. However, the ratio of percent temperature decline verses percent surface area increase is in favor of height. This suggests that, in general, it would be more cost effective to increase the tower's height rather than cross sectional area.

Several aspects of the experimentation and simulation could be improved on. For example, simulation results should be compared to multiple experimental configurations of the tower, building space and internal heat gain. The tower air flow calculations only consider pressure difference due to the difference in temperature between the inside and outside air. Wind-induced pressurization and venturi effects at the outlet of the wind tower should also be considered. These effects could be measured by placing the tower in a wind tunnel. In addition, the placement of the wind tower opening and air inlets into the building should be considered. Finally, the model should include energy storage effects in the thermal mass of the building. Perhaps the best way to incorporate all of these issues into a single model would be to use computational fluid dynamics.

Finally, the building could be modeled with energy simulation software to help determine how much energy would be used for traditional air conditioning. These results could help determine the economic feasibility of wind towers.

REFERENCES

Hetrick, B. and Kashuk, M., 1996, "Experimental Characterization of Temperature and Air Flow in Passively Ventilated Buildings", University of Dayton Independent Study, Dayton, OH, April 26, 1996.

Jones, J. and West, A., 2001, "Natural Ventilation and Collaborative Design", *ASHRAE Journal*, November 2001.

Karla, E. and King, W., 1995, "The Effect of Orifice Parameter Variation on a Passively Ventilated Building", University of Dayton Senior Lab, Dayton, OH, December 15, 1995.

Short, Alan, 1995, "Case Studies of Non-Domestic Natually Conditioned Buildings – Design and System Trends for the Future", Global Engineering Conference, Vancouver, BC, May 3-5.